

Modeling and Simulation of an UAS Collision Avoidance Systems

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Abstract

This paper describes a **Modeling and Simulation of an Unmanned Aircraft Systems (UAS) Collision Avoidance System**, capable of representing different types of scenarios for UAS collision avoidance. Commercial and military piloted aircraft currently utilize various systems for collision avoidance such as Traffic Alert and Collision Avoidance System (TCAS), Automatic Dependent Surveillance-Broadcast (ADS-B), Radar and Electro-Optical and Infrared Sensors (EO-IR). The integration of information from these systems is done by the pilot in the aircraft to determine the best course of action. In order to operate optimally in the National Airspace System (NAS) UAS have to work in a similar or equivalent manner to a piloted aircraft by applying the principle of “detect-see and avoid” (DSA) to other air traffic. Hence, we have taken these existing sensor technologies into consideration in order to meet the challenge of researching the modeling and simulation of an approximated DSA system. A Schematic Model for a UAS Collision Avoidance System (CAS) has been developed in a closed loop block diagram for that purpose. We have found that the most suitable software to carry out this task is the Satellite Tool Kit (STK) from Analytical Graphics Inc. (AGI). We have used the Aircraft Mission Modeler (AMM) for modeling and simulation of a scenario where a UAS is placed on a possible collision path with an initial intruder and then with a second intruder, but is able to avoid them by executing a right turn maneuver and then climbing. Radars have also been modeled with specific characteristics for the UAS and both intruders. The software provides analytical, graphical user interfaces and data controlling tools which allow the operator to simulate different conditions. Extensive simulations have been carried out which returned excellent results.

1. Introduction

In 2007, NASA-Kennedy Space Center (KSC) Applied Technology Directorate postured itself to support/develop an Unmanned Aircraft Systems (UAS) program to support future missions at KSC, Patrick Air Force Base (PAFB), and Cape Canaveral Air Force Station (CCAFS). This was a joint program effort with the Air Force 45th Space Wing. This program supports near-term goals of U.S. national space launch bases and ranges for providing enhanced mission support from mobile aerial platforms with tracking and surveillance capabilities. The UAS program would incorporate system development of an optimal UAS collision avoidance system to maximize the protection of personnel, property, and other aircraft.

UAS are under continuous research and development needed for an ample variety of assignments, such as zone monitoring, vehicle tracking, environmental observation, military surveillance and many other applications.

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Before the FAA permits widespread integration of UAS in the NAS, UAS will need to be fitted with a reliable collision avoidance system. According to the Government Accountability Office (GAO), to date, no such system has been developed to meet the FAA's requirement that UAS demonstrate an "equivalent level of safety, comparable to see-and-avoid requirements for manned aircraft". Consequently, KSC is working with government and industry partners to research and develop an optimal CAS.

Several researchers are investigating and studying this interesting field. One important study regarding the Field of Regard (FOR) and Elevation Field of Regard (EFR) was conducted by NASA's Environmental Research Aircraft and Sensor Technology (ERAST) Program [1]. The study assumed a head on encounter between two aircraft in leveling flight and recommended a FOR of ± 110 degree azimuth and EFR of ± 15 degree elevation. Some studies have since adopted those values, but other researchers consider that additional analysis is needed and some have considered higher values [2]. A Z-Basic prediction algorithm for aircraft ground based collision avoidance system was studied by Dear and Sherif [3]. A study by Han and Bang [4] on a collision avoidance law based upon conventional Proportional Navigation guidance law was proposed. Coulter [5] has done sensitivity analysis and performance parameters trade studies in order to establish Collision Avoidance requirements. Further, a safety analysis methodology for unmanned aerial vehicle (UAV) collision avoidance system performance has been studied by Kuchar [6].

Commercial and military piloted aircraft currently utilize various systems for collision avoidance such as Traffic Alert and Collision Avoidance System (TCAS), Automatic Dependent Surveillance-Broadcast (ADS-B), Radar, and Electro-Optical and Infrared Sensors (EO-IR). The integration of information from these systems is done by the pilot in the aircraft to determine the best course of action. Hence, we are taking these existing technologies into consideration to meet this challenge of research on the modeling and simulation of an approximated DSA system.

Schematic Model for a UAS Collision Avoidance System (CAS)

A Schematic Model for a UAS Collision Avoidance System (CAS) has been developed in a closed loop block diagram: Starting with a **Controller**, we have considered four types of sensors: **Radar, Electro Optical-Infrared Sensors (EO-IR), ADS-B and TCAS**. The sensors are followed by an **Adaptive Control Algorithm and Filter, Autopilot** and also the **Aircraft Dynamics** -- whose output (actual aircraft heading) is being fed through a transducer to a summation point to be compared with the desired aircraft heading -- giving an error signal that goes as an input to the **Controller**. A Schematic Diagram is shown in Fig. 1. **Figure1. Schematic Model for a UAS Collision Avoidance System (CAS)**

We have chosen a Predator UAS for our modeling and simulation collision avoidance system scenario because it is one of the most popular and well known high-tech aircraft. It is capable of reconnaissance, combat and support roles in the most difficult battles.

The Predator UAS is a medium-altitude, long range aircraft that operates much like any other small plane. It has a Rotax 914, four-cylinder, four-stroke, 101 horsepower engine that turns the main drive shaft, which in turns rotates the Predator's two-blade, variable-pitch pusher propeller. The rear-mounted propeller provides both drive and lift. It reaches airspeeds over 220 kt (407 km/hr). An additional lift provided by the aircraft's 48.7-foot (14.8-meter) wingspan, allows the Predator to reach altitudes of up to 25,000 feet (7,620 meters). The slender fuselage and inverted-V tails help the aircraft with stability, and a single rudder housed beneath the propeller steers the craft.



Figure 3. Predator RQ-1/MQ-1

The requirements

- i) Modeling and simulating a UAS Collision Avoidance System.
- ii) Minimum separation distance: A conflict is defined as another aircraft that will pass less than 500 feet, horizontally or vertically, from the UAS [7]. Traditionally, separation of aircraft is based on a distance of 5 NM, but for two high speed aircraft 5 NM apart flying head to head, there is little time to resolve that situation [8], hence this scenario has to be adjusted accordingly.
- iii) Threat detection: Warning of approximated traffic is considered to be 45 seconds before Time to Closest Point of Approach (CPA), which is called **miss distance**. Resolution Advisory (RA): if the situation deteriorates at some 30 seconds before CPA, it is a **critical range** and a Resolution Advisory (RA) is issued and evasive action maneuver is required [9].
- iv) Azimuth Field of Regard (AFOR): $\pm 110^\circ \pm 60^\circ$ (objective/threshold) of the on board sensor system, horizontal with respect to the longitudinal axis of the UAS, and Elevation Field of Regard (EFOR): $\pm 30^\circ \pm 10^\circ$ (objective/threshold), vertical with respect to the flight path at normal cruise speed, and provides sufficient coverage to enable detection of conflicting air traffic during expected maneuvers.
- v) The model shall be dynamic, capable of representing different types of scenarios under varying parameter requirements.

2. Problem Statement

In order to operate optimally in the National Air Space (NAS) UAS have to work in a similar or equivalent manner to a piloted aircraft applying the principle of "Detect-See and Avoid" (DSA) to other air traffic. Therefore, the integration of UAS into the NAS requires extensive research in developing new methods and technologies to ensure the detection and avoidance of other aircraft.

There are two types of air traffic systems: i) cooperative and ii) non-cooperative.

In the first case the cooperative traffic broadcasts its position using a transponder (commercial airplanes and helicopters); while in the second case the non-cooperative traffic does not broadcast information, such as buildings, parachutists and private aircraft.

Commercial and military piloted aircraft currently utilize various systems for collision avoidance such as Traffic Alert and Collision Avoidance System (TCAS), Automatic Dependent Surveillance-Broadcast (ADS-B), Radar, and Electro-Optical and Infrared Sensors (EO-IR). We are taking these existing technologies into consideration to meet the challenge of researching the modeling and simulation of an approximated DSA system.

This project also offered an opportunity to evaluate the capability of STK to simulate this complex scenario.

3. System Implementation

We have developed and implemented a computer-based simulation of a UAS Collision Avoidance System using the interactive graphical user interface program STK from Analytical Graphics Inc. (AGI), which was found to be the most suitable software to carry out this task.

We have used the Aircraft Mission Modeler (AMM) for modeling and simulation of a scenario where a UAS is placed on a possible collision path, with a first intruder and then with a second intruder, but is able to avoid them by executing a right turn maneuver and then climbing. Radars have also been modeled with specific characteristics for the UAS and both intruders. Extensive simulations have been carried out and excellent results have been obtained.

As the analysis of the whole system is difficult to model due to the strongly complex coupled nature of its components and due to some limitations of the software, we have started modeling the system by considering radar first. We have chosen a Synthetic Aperture Radar (SAR), which stems from the military requirement to be able to fly during the day and at night in all weather conditions. Combining the atmospheric penetration capabilities of radar and the high resolution similar to images from an optical sensor under ideal scenarios, a SAR offers the ability to gather radar imagery of near photographic quality in all conditions. In our computer-based simulation, measures have been taken in a controlled manner that give the full range of SAR performance.

Thus, we have modeled a scenario, where we have considered a Predator RQ-1 (UAS) and two Intruders (Intruder 1 and Intruder 2), which are also UAS. They are placed in the airspace at different latitudes and longitudes. In the first encounter, Intruder 1 is approaching laterally to the right of the UAS at the same altitude (10,000 ft) on a possible collision path at a certain point (CPA). The UAS radar tracks Intruder 1 and vice versa, then it avoids the intruder with a right turn maneuver and returns to its original flight path. After a certain time period the second intruder unexpectedly appears and it is also being tracked by the UAS sensor, similarly Intruder 2 does the same with the UAS. When it is approaching a possible collision path (CPA) the UAS starts climbing (from 10,000 to 13,000 ft) over the intruder, then returns to its original heading.

Several measurements have been taken between the UAS and the intruders considering the sensors (radars), such as:

Time (T), Latitude (La) and Longitude (Lo); Range (R) and Relative Speed (RS); Azimuth (Az), Elevation (E) and Range (R), and calculating the time to the CPA. Results are presented and discussed.

UAS Basic Performance Parameters

Predator RQ-1A

Ceiling: 25,000 ft
True Air Speed: 180 knots (kt)
Default Cruise MSL Altitude: 10,000 ft (for simulation)
Climb/Descend Vertical Speed: 2,000 ft/min
Takeoff/Landing Speed 100 kt
Fuel Flow: 500lb/hr
Bank Angle: 18 degree (for simulation)

Intruder 1 Basic Performance Parameters

Predator MQ-9B

Ceiling: 25,000 ft
True Air Speed: 180 knots (kt)
Default Cruise MSL Altitude: 10,000 ft (for simulation)
Climb/Descend Vertical Speed: 2,000 ft/min
Takeoff/Landing Speed 100 kt
Fuel Flow: 500lb/hr
Bank Angle: 30 degree (default for simulation)

Intruder 2 Basic Performance Parameters

Predator RQ-1

Ceiling: 25,000 ft
True Air Speed: 180 knots (kt)
Default Cruise MSL Altitude: 10,000 ft (for simulation)
Climb/Descend Vertical Speed: 2,000 ft/min
Takeoff/Landing Speed 100 kt
Fuel Flow: 500lb/hr
Bank Angle: 30 degree (default for simulation)

4. Simulation and Analysis of Results

Extensive simulations were carried out and measurements have been obtained in order to track the UAS and the intruders on a possible collision path. Also, the sensors (radars) have been used for that purpose, considering the most suitable parameters for tracking of the UAS against the intruders and vice versa. In another words, we have full control of changing and varying

different parameters dynamically and observing the response of the system under different conditions, using the STK software.

UAS Predator RQ-1A-To-Intruder 1 Predator MQ-9B

22 May 2008 15:16:23

Aircraft-UAS-To-Aircraft-Intruder1: Access Summary Report

UAS-To-Intruder1

Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	1 Jul 2007 12:19:38.962	1 Jul 2007 12:20:08.068	29.106

Global Statistics

Min Duration	Max Duration	Mean Duration	Total Duration
1 Jul 2007 12:19:38.962 - 1 Jul 2007 12:20:08.068	1 Jul 2007 12:19:38.962 - 1 Jul 2007 12:20:08.068	1 Jul 2007 12:19:38.962 - 1 Jul 2007 12:20:08.068	1 Jul 2007 12:19:38.962 - 1 Jul 2007 12:20:08.068
29.106	29.106	29.106	29.106

Table 1.1 Access Summary UAS-To-Intruder 1

22 May 2008 16:50:11

Aircraft-UAS-To-Aircraft-Intruder1: Inview Azimuth, Elevation, & Range

UAS-To-Intruder1

Time (UTCG)	Azimuth (deg)	Elevation (deg)	Range (nm)
1 Jul 2007 12:19:38.962	293.604	-0.223	7.999999
1 Jul 2007 12:19:57.404	280.661	-0.216	7.882833
1 Jul 2007 12:20:08.068	273.220	-0.210	7.999989

Global Statistics

Min Elevation	Max Elevation	Mean Elevation	Min Range	Max Range	Mean Range
1 Jul 2007 12:19:38.962	1 Jul 2007 12:20:08.068	1 Jul 2007 12:19:38.962 - 1 Jul 2007 12:20:08.068	1 Jul 2007 12:19:53.515	1 Jul 2007 12:19:38.962	1 Jul 2007 12:19:38.962 - 1 Jul 2007 12:20:08.068
-0.223	-0.210	-0.216	7.873751	7.999999	7.960941

Table 1.2 Inview AER UAS-To-Intruder 1

In Table 1.1 an Access UAS-Intruder 1 Summary Report has been resolved, which reveals the initial time and the end time for when the UAS radar senses the presence of Intruder 1 within its range. The duration in time that the intruder is being tracked by the radar of the UAS is also listed. In Table 1.2 we see the minimum range (7.873751 nm), which is at the Critical Point of

Approach (CPA), and the Azimuth and Elevation of the UAS with respect to the intruder. Figures 1.1-1.6 show sequences of the UAS and Intruder 1 flight paths and the point of possible collision, including the radar lobes of tracking one to each other. The maneuvers that the UAS has to do include banking and turning right to avoid the collision and then coming back to its original flight path. Pictures in 3-D (Figures 1.7-1.8) of the UAS (Predator) and Intruder 1 have also been obtained for these sequences, that show the time when the close encounter is happening, the range in nautical miles and the relative speed (kt) of the UAS with respect to the Intruder 1. These values can be monitored during the whole simulation.



Figure 1.1 UASRADARINTR1_2DP



Figure 1.2 UASRADARINTR1A_2DP



Figure 1.3 UASRADARINTR1B_2DP

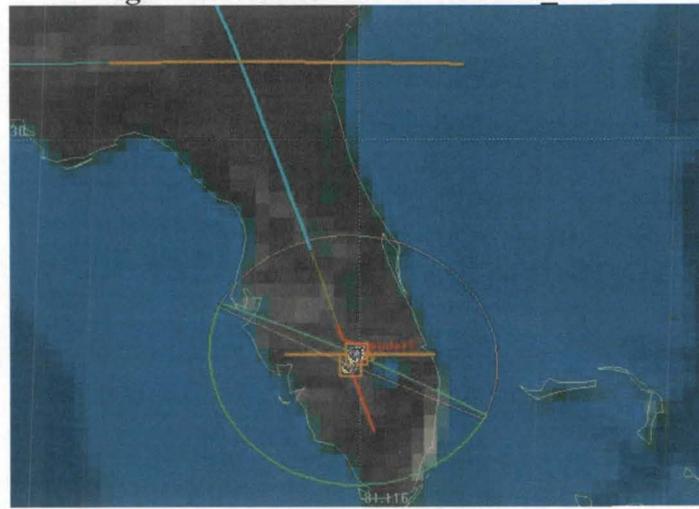


Figure 1.4 UASRADARINTR1C_2DP

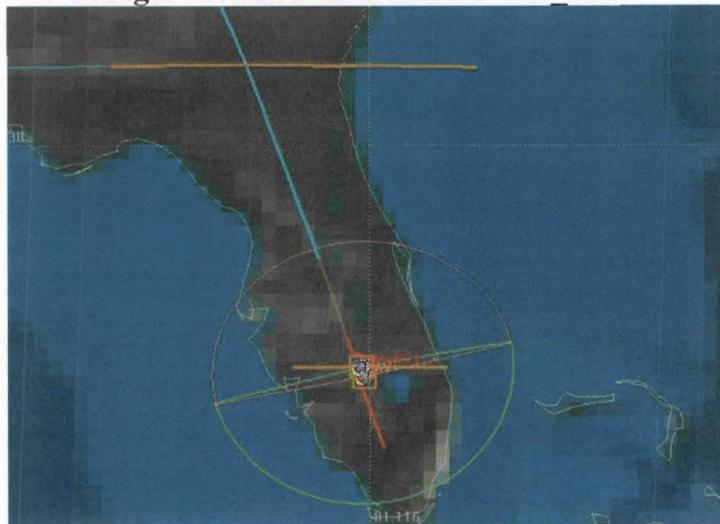


Figure 1.5 UASRADARINTR1D_2DP

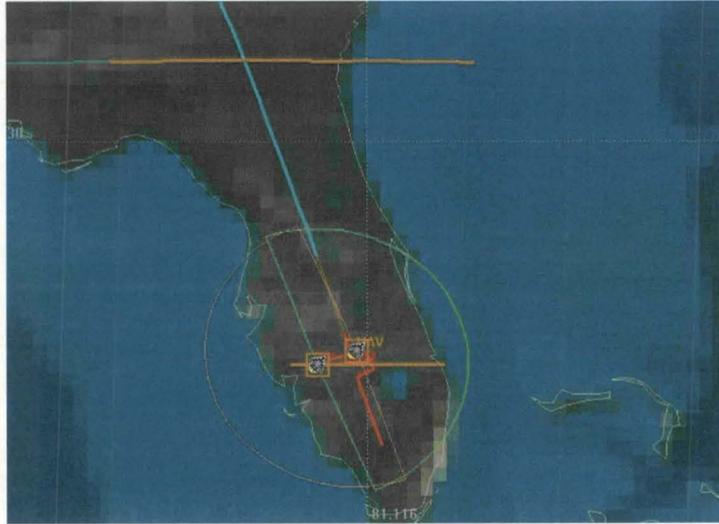


Figure 1.6 UASRADARINTR1E_2DP

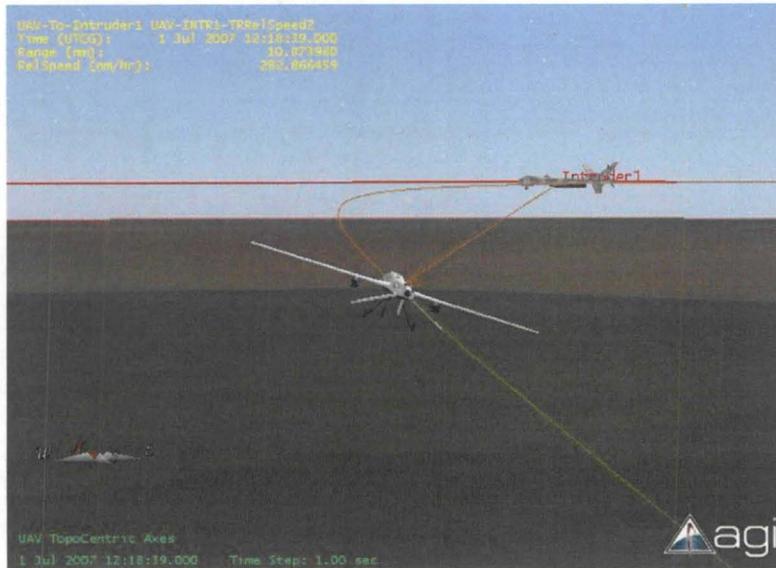


Figure 1.7 UAS-INTR1A_3DP

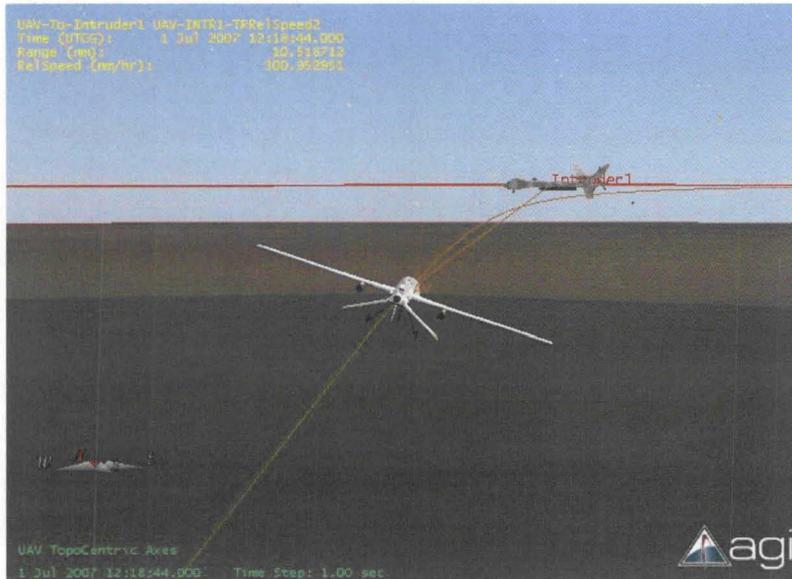


Figure 1.8 UAS-INTR1B_3DP

UAS Predator RQ-1A-To-Intruder 2 Predator RQ-1

22 May 2008 15:42:33

Aircraft-UAS-To-Aircraft-Intruder2: Access Summary Report

UAS-To-Intruder2

Access	Start Time (UTC)	Stop Time (UTC)	Duration (sec)
1	1 Jul 2007 13:48:46.659	1 Jul 2007 13:49:21.305	34.646

Global Statistics

Min Duration	1	1 Jul 2007 13:48:46.659	1 Jul 2007 13:49:21.305	34.646
Max Duration	1	1 Jul 2007 13:48:46.659	1 Jul 2007 13:49:21.305	34.646
Mean Duration				34.646
Total Duration				34.646

Table1.3 Access Summary UAS-To-Intruder 2

22 May 2008 16:45:42

Aircraft-UAS-To-Aircraft-Intruder2: Inview Azimuth, Elevation, & Range

UAS-To-Intruder2

Time (UTC)	Azimuth (deg)	Elevation (deg)	Range (nm)
1 Jul 2007 13:48:46.659	344.926	-5.392	3.000001
1 Jul 2007 13:49:09.097	319.031	-8.231	2.838590
1 Jul 2007 13:49:21.305	305.170	-9.094	2.999957

Global Statistics

Min Elevation			
1 Jul 2007 13:49:21.305	305.170	-9.094	2.999957
Max Elevation			
1 Jul 2007 13:48:46.659	344.926	-5.392	3.000001
Mean Elevation		-7.572	
Min Range			
1 Jul 2007 13:49:03.983	325.132	-7.695	2.822693
Max Range			
1 Jul 2007 13:48:46.659	344.926	-5.392	3.000001
Mean Range			2.946183

Table1.4 Inview AER UAS-To-Intruder 2

Similarly, in Table 1.3 an Access UAS-Intruder 2 Summary Report has been found, where we may see the time when this is happening and the duration in time (34.646 sec) that the intruder is being tracked by the radar of the UAS. Also, in Table 1.4 we may see the minimum range (2.822693 nm) that the intruder is approaching to the UAS when it is climbing, and the Azimuth and Elevation of the UAS with respect to the intruder. Figures 2.1-2.5 shows sequences of the UAS and Intruder 2 flight paths and the point of possible collision, including the radar lobes of tracking one to each other. Besides the maneuvers that the UAS has to do when it is approaching to a possible collision path (CPA) the UAS starts climbing (from 10,000 to 13,000 ft) over the intruder, then returns to its original heading. Pictures in 3-D (Figures 2.6-2.7) of the UAS (Predator) and Intruder 2 have also been obtained for these sequences, where it may be seen the time when the close encounter is happening, the range in nautical miles and the relative speed (kts) of the UAS with respect to the Intruder 1. These values can be monitored during the whole simulation.

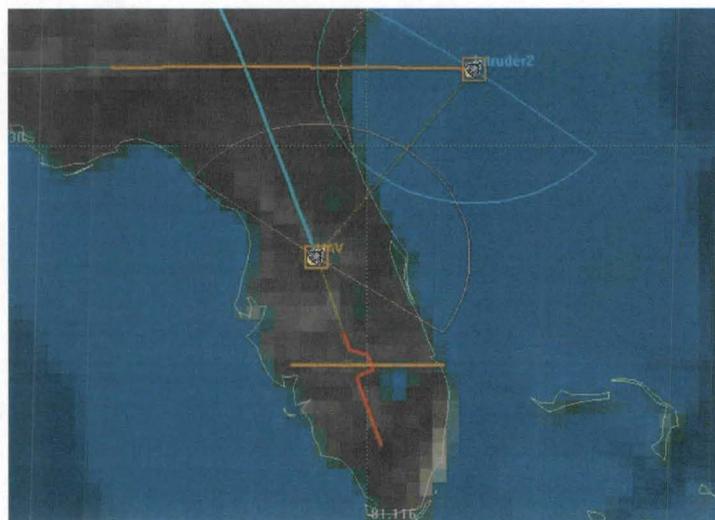


Figure 2.1 UASRADARINTR2A_2DP

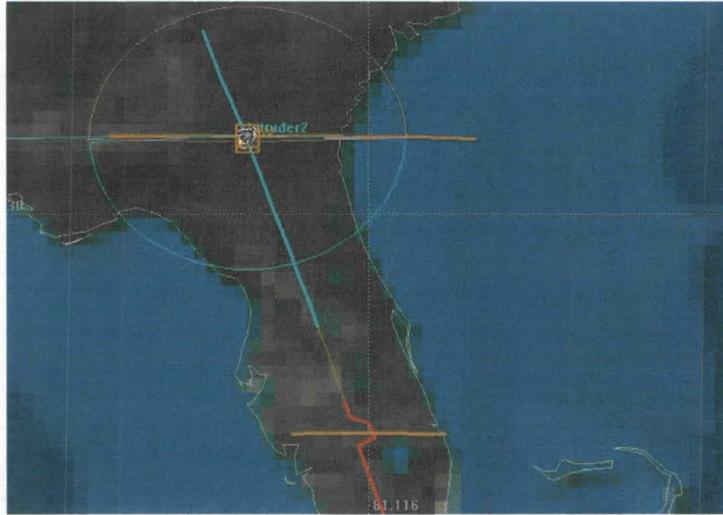


Figure 2.2 UASRADARINTR2B_2DP



Figure2.3 UASRADARINTR2C_2DP



Figure2.4 UASRADARINTR2D_2DP

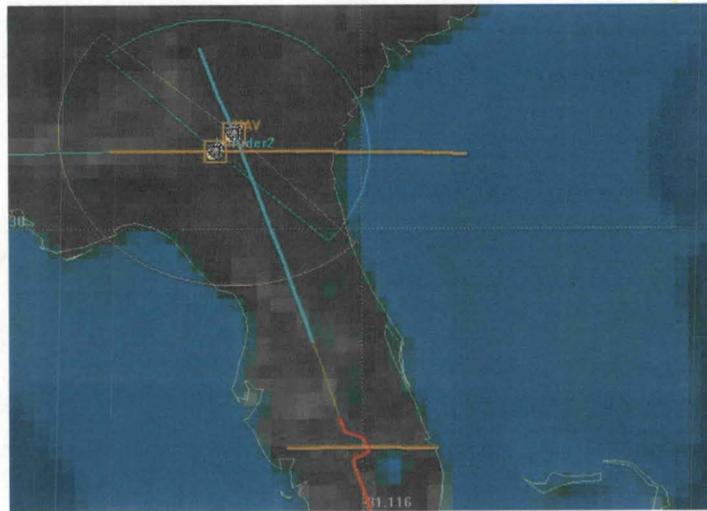


Figure 2.5 UASRADARINTR2E_2DP

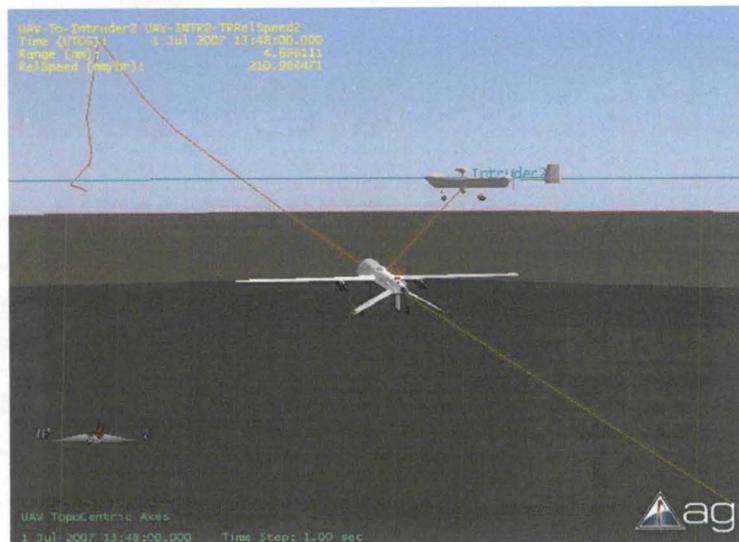


Figure 2.6 UAS-INTR2B_3DP

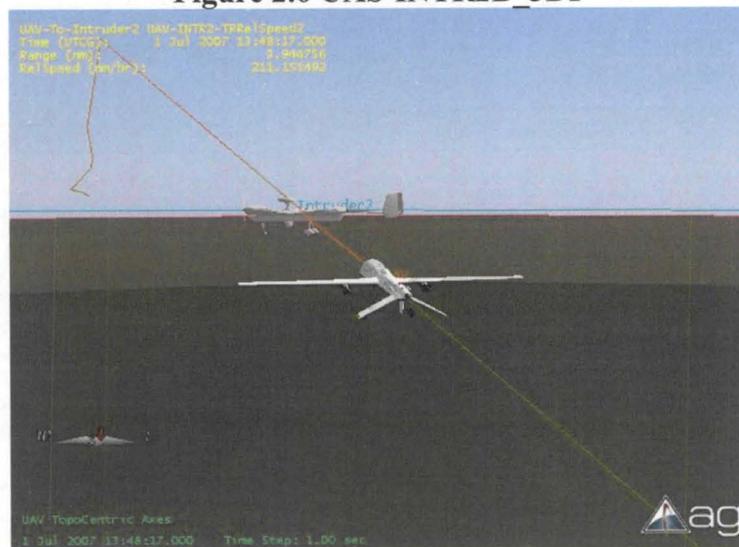


Figure 2.7 UAS-INTR2C_3DP

Mathematical Model Equations

Some useful mathematical model equations for modeling and simulation of a scenario where a UAS is placed on a possible collision path with an intruder are given in the Appendix as reference.

Boundaries and Limitations

- a) The simulation is limited to modeling and simulation of a scenario where UAS is placed on a possible collision path with an initial intruder and then with a second intruder and avoids them by executing a right turn maneuver and then climbing.
- b) The Radars have also been modeled with specific characteristics for the UAS and both intruders.
- c) As the analysis of the whole system is difficult to model due to the strongly complex coupled nature of its components and due to some limitations of the software, we have started modeling the system by considering radar first.
- d) We have chosen a Synthetic Aperture Radar (SAR), which stems from the military requirement to be able to fly during the day and at night in all weather conditions.
- e) In our computer-based simulation, measures have been taken in a controlled manner that gives the full range of SAR performance.
- f) We have full control of changing aircraft parameters, latitude, longitude, range, altitude, speed and position, for what the STK software provides to do these changes.
- g) The software does not include TCAS and ADS-B sensors.
- h) The software does not include an autopilot model.

6. Conclusions

- i) Ideally, a UAS is expected to automatically sense that it is on a collision path with cooperative systems such as commercial airplanes and helicopters; and non-cooperative systems such as buildings, parachutists, and private aircraft. The UAS is then expected to autonomously deviate from its planned flight path to avoid collision.
- j) A Schematic Model for a UAS Collision Avoidance System (CAS) has been developed in a closed loop block diagram for that purpose.
- k) We have found that the most suitable software to carry out this task was from Analytical Graphics Inc. (AGI), which developed the Satellite Tool Kit (STK). It is an interactive graphical user interface program which proved to be a great tool for rapid development and implementation of a computer model of the aircraft, and was used for that purpose.
- l) We have use the Aircraft Mission Modeler (AMM) for modeling and simulation of a scenario where a UAS is placed on a possible collision path with an initial intruder and then with a second intruder and avoids them by executing a right turn maneuver and then climbing.
- m) Radars have also been modeled with specific characteristics for the UAS and both intruders.

- n) The software provides analytical, graphical user interface and data controlling tools which allow the operator to simulate different conditions.
- o) Extensive simulations have been carried out and excellent results have been obtained.

7. Future Research

Possible ideas for future research include:

- a) Add various types of sensors such as Traffic Alert Collision Avoidance System (TCAS) and Automatic Dependent Surveillance Broadcast (ADS-B) for a combined solution that will automatically and autonomously control the unmanned aircraft's flight maneuvers comparable to those of manned aircraft.
- b) To maximize the protection of personnel, property, and other aircraft in the National Airspace through the investigation and development of an optimal UAS collision avoidance system.
- c) To collaborate with NASA as an academic partner. The goal of an optimum UAS collision avoidance system is currently an international pursuit. Consequently, NASA-KSC is working with the Air Force, Navy, and other government and industry partners to research and develop such a system.
- d) One significant challenge will be to develop an intelligent adaptive control system which will avoid in-air collisions. Ultimately, the goal is to employ the UAS autonomously in settings such aerial photography to assist in disaster mitigation, crop monitoring, weather monitoring and so forth. In the military field, the UAS can perform intelligence, surveillance and reconnaissance missions.
- e) Another significant challenge will be the requirement for extensive development and deployment of an advanced automatic control systems throughout the airframe. This means, that the integration of UAS into civil airspace requires new technical methods of ensuring collision avoidance.

APPENDIX

Useful Mathematical Equations

Define:

Aircraft turn radius (R):

$$R = \frac{V^2}{g \tan \phi}$$

Where:

V: aircraft velocity

Φ : bank angle

g: acceleration of gravity

Turn rate (ω) in degrees/sec:

$$\omega = \left(\frac{g \tan \phi}{V} \right) \left(\frac{360}{2\pi} \right)$$

Minimum detection range (MDR):

$$\text{MDR} = (V_{\text{UAS}} + V_{\text{INT}}) \times (T_d + T_{\text{CPA}} + T_{\text{NWT}} + T_{\text{AM}})$$

Where:

V_{UAS} = UAS velocity

V_{INT} = Intruder velocity

T_d = Detection time

T_{CPA} = Time to closest point of approach (CPA)

T_{NWT} = Nominal warning time

T_{AM} = Time for avoidance maneuver

Linear time (T_a) to closest point of approach:

$$T_a = \left(\frac{r^2 - m_a^2}{-r \dot{r}} \right)$$

Where:

r = range

\dot{r} = range rate

m_a = linear miss distance

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